Chapter Seven

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Summary

In the preceding chapters, we have laid out a plan for large-scale U.S. measurements of CO$_2$ in the fluid realms of the surface Earth. The measurements are formulated to allow us to track the distribution of fossil fuel CO$_2$ in the oceans and atmosphere, improve our understanding of underlying controls on inventories and fluxes, and to advance our ability to predict the future distribution of fossil CO$_2$ in the oceans, atmosphere, and land biosphere. This document represents the implementation plan for the large-scale CO$_2$ observing component of the U.S. Carbon Cycle Science Plan.

The implementation plan recommends an integrated study of CO$_2$ accumulation and transfer in the atmosphere, the surface ocean, and the ocean interior. The atmosphere is of interest as the medium from which CO$_2$ is lost to both the land biosphere and the oceans. It is also, of course, the reservoir that impacts climate via the greenhouse effect. The sea surface is of interest as the interface between atmosphere and ocean interior. The interior is of interest as the ultimate repository of most anthropogenic CO$_2$.

A number of common features exist in the programs that we recommend for each of these realms. First, plans for each realm involve analytical and other advances in instrumentation. The atmospheric plan calls for development of an advanced CO$_2$ analyzer that would be the keystone of several new field efforts. Sea surface and ocean interior plans call for the development of autonomous sensors that will provide continuous long-tem measurements on a variety of platforms. Perhaps foremost among these seawater instruments are ones that will measure two variables in the CO$_2$ system.

Second, the backbone of each observing system is an ongoing network aimed at comprehensively documenting the evolving CO$_2$ distribution. The specific observing plan for each realm depends on the accessibility to sampling and the time and space scales of variability. Observations for the atmosphere involve continued sampling at remote stations as well as an intensive program of aircraft sampling. Much of the sampling is to be done on synoptic timescales, with continuous sampling on tall towers supporting the study of boundary layer mixing. Sea surface pCO$_2$ studies will be focused around volunteer observing ships (VOS) making continuous measurements on repeat crossings. These will be supplemented by moored autonomous instruments and shipboard sampling at traditional time series study stations. The sea surface observations will access all timescales from diurnal, to seasonal, to interannual. Accessibility is much poorer than for atmospheric measurements, but mean values and variability can be characterized with fewer observing platforms. Ocean interior CO$_2$ concentrations are most difficult to measure, while changing most slowly. We recommend observing ocean interior CO$_2$ with repeat ocean hydrographic sections occupied once per decade. As is the case for sea surface studies, these will be supplemented with time series measurements at fixed locations. The combined interior data

set will record both interannual variability and the continuing accumulation of anthropogenic CO_2.

A third common feature is that measurements in all three realms will have process content related to biogeochemistry and ocean/atmosphere physics. Atmospheric studies emphasize continental measurements in the lower atmosphere that reflect the dynamics of boundary layer mixing, given the diurnal cycle of CO_2 uptake and release by the biosphere. Sea surface CO_2 studies include two important process components. The first involves measurements of chemical and isotopic tracers constraining net and gross production rates. These results, in turn, inform us about the quantitative impact of upper ocean biology on sea surface TCO_2 and pCO_2. The second is the study of gas exchange coefficients and their dependence on wind speed or a related property. These studies will allow us to reduce the large uncertainties this term currently introduces into air-sea CO_2 fluxes. Ocean interior studies address ocean physics issues by providing information on the distribution of halocarbons and anthropogenic CO_2. These data challenge tracer transport models that predict patterns of these properties. In addition, information on interannual variability in the atmosphere, surface ocean, and interior ocean holds key process-level information: in each case, it reflects the biological response to changes in physical forcing (expressed as weather/climate on land, and mainly as mixing in the ocean).

The fourth, related, common point is the essential interaction between data collection and modeling. To deduce carbon fluxes from CO_2 distributions, we need models describing both physical transport and interactions with the biosphere. Neither the physical nor biogeochemical models are adequate in any of the three realms. Perhaps the most satisfactory models concern upper ocean physics, while the least satisfactory describe remineralization of biogenic matter in the thermocline (these nominations could certainly be debated). The models themselves need to be technically upgraded to give better inherent descriptions of the processes they represent. As well, models need to incorporate results of observations, described above, so that they correctly represent rates of all important biogeochemical and physical processes. Thus, for all three realms, we envision an interactive process in which models are used to interpret data, and data are used to improve models. Simultaneously, physical and biogeochemical models will become more sophisticated in basic approach. Thus, for example, in all three realms, there is a progression from one-dimensional to two- and three-dimensional models; from steady-state to time-dependent models; and from forward models, to inverse models, and on to data assimilation models. Analogously, there is a progression from empirical parameterizations of biogeochemical processes to quantitative representations of fundamental rate processes.

Fifth, progress in each realm requires interfacing our large-scale observations with small-scale studies of fundamental biosphere processes that are being independently planned. Studies in all three realms also need to deal with the problem of scaling. One aspect of this problem is experimental. This aspect involves the need to study processes at scales ranging from the level of organisms, to that of local and coherent ecosystems, to scales of continents and ocean basins, to the globe. This plan deals with the larger

scales. However, success requires interfacing with programs to study fundamental processes on the scales of organisms and local ecosystems. This topic, implicit rather than explicit in our recommendations, will receive attention as process studies and observations progress from planning to action. A second aspect of the scaling problem relates to models. Models must be able to describe CO$_2$ fluxes and distributions at the large scale in a way that reflects the fundamental processes observed in organism/ecosystem studies of the biosphere, as well as the basic transport processes of the atmosphere and oceans. A related issue, both implicit and explicit in this document, involves international cooperation. Implementation of the various national plans needs to be coordinated so that the international effort is synergistic.

Sixth, the recommended studies in each realm are redundant wherever possible. We regard this characteristic as essential, since each approach gives fluxes with large uncertainties. The most important point of overlap concerns rates of CO$_2$ uptake at the sea surface. Atmospheric measurements, sea surface pCO$_2$ measurements, and ocean interior measurements all constrain rates of CO$_2$ uptake by the oceans at basin or smaller scales. Comparing these redundant measurements will be an important focus of the program. Good agreement will verify the independent estimates. It would also validate continental CO$_2$ uptake estimates based on atmospheric data alone.

Finally, the studies we recommend have the dual objectives of characterizing distributions and fluxes in each realm as well as gaining process level insight. The two together allow us to track evolving inventories of anthropogenic CO$_2$ while also deepening our understanding of basic biogeochemical processes, as needed for prediction.